Interplanetary Alfvén Waves, HILDCAAs, Acceleration of Magnetospheric Relativistic "Killer" Electrons and Auroral Zone Heating

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Abstract

We review one aspect of space weather, high-speed solar wind streams (HSSs) emanating from solar coronal holes. We will trace the important plasma features from the Sun to the Earth's magnetosphere and ionosphere. In particular we will discuss the formation of Alfvén waves in interplanetary space, the effects of magnetic reconnection between the southward component of the Alfvénic wave magnetic fields with the Earth's magnetopause fields, the eventual acceleration of ~ MeV electrons and loss of these particles to the ionosphere and atmosphere.

Introduction

Space Weather is the topic of the Sun's effect on the heliosphere and planetary magnetospheres and ionospheres. There are solar flare associated coronal mass ejections (CMEs) that cause geomagnetic storms when these giant plasma blobs hit the Earth's magnetosphere (Gonzalez et al., 1989, 1994; Tsurutani et al., 2003). Super intense magnetic storms (SYM-H < -250 nT) can cause power outages at Earth (Royal Acad. Eng., 2013), but it has been recently argued that it is most probably supersubstorms within the superstorms that are the actual cause (Tsurutani et al., 2015).

In this paper we will review the latter topic, the formation of interplanetary Alfvén waves, their effect on the magnetosphere and the acceleration of relativistic electrons and their precipitation into the ionosphere and atmosphere. Solar coronal hole high-speed solar wind streams (HSSs) cause ~27 day recurrent moderate intensity (-50 nT > SYM-H > -100 nT) geomagnetic storms and high-intensity long-duration continuous AE activity or HILDCAAs (Tsurutani and Gonzalez, 1987; Tsurutani et al., 2006; Hajra et al. 2013). HILDCAAs are well-associated with the acceleration of relativistic MeV killer electrons (Hajra et al., 2014b; 2015) which can damage Earth orbiting spacecraft satellites (Wrenn, 1995; Horne et al., 2013).

Method

Studies of space weather typically involve the use of data from NASA, ESA and NOAA spaceborne instrumentation and ground based geomagnetic indices. In this paper we will cite results taken from publications which have used the ISEE-3, ACE, Cluster, Ulysses, IMP-8, HELIOS and GOES spacecraft data. Ground-based geomagnetic indices such as AE, Dst and SYM-H are obtained from the Kyoto University World Data Center website. The interplanetary data were obtained from OMNI website. This review will focus on the Space Weather contributions made by members of the Brazilian Geophysical Society.

Results

Interplanetary Alfvén waves

Interplanetary Alfvén waves were discovered by Coleman (1968) and Belcher and Davis (1971) using plasma and magnetic field measurements on the Mariner 2 and 5 NASA spacecraft, respectively. These large amplitude waves were noted to occur in HSSs and were shown to be propagating outward away from the Sun (Belcher and Davis, 1971). Since the HSS has velocities varying from ~500 to 800 km/s and the Alfvén wave speed is only ~70 km/s, the waves are convected by the solar wind.

The large amplitude Alfvén waves have been noted to evolve in space. They have been shown to phase-steepen in space. Figure 1 shows an example of 3 cycles of the wave given in minimum variance coordinates (Smith and Tsurutani, 1975). It can be seen that the waves are not sinusoidal, but slowly rotate ~180° in phase and then suddenly rotate back 180°. This type of wave polarization is called "arc polarization" because the tip of the wave magnetic vector rotates in an arc and then back.

Alfvén wave phase-steepening provides both high frequency wave power (the phase-steepened edge) and low frequency power (the trailing portion of the wave). Because Alfvén waves are the only ever present wave mode detected in interplanetary space, this phase-steepening process may be the main contributor of "interplanetary turbulence" (Tsurutani et al., 2005).

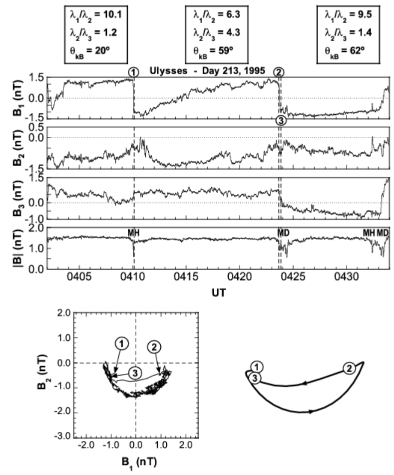

Figure 1. Three cycles of Alfvén waves. The waves are phase-steepened, are spherical and have arc-polarizations. Taken from Tsurutani et al. (2002a).

What is arc polarization? Figure 2 shows a schematic where the wave magnetic field perturbation vector rotates on the surface of a sphere. Three types of polarizations are illustrated: circular, elliptical and arc. These Alfvénic arc polarized waves are the nonlinear extension of linearly polarized Alfvén waves. Waves where the magnetic field vector rotates on the surface of a sphere have constant magnetic field magnitudes, and are thus spherical waves. Waves detected close to their origins will be spherical in nature. When the waves have propagated long distances from their origin they become planar in nature.

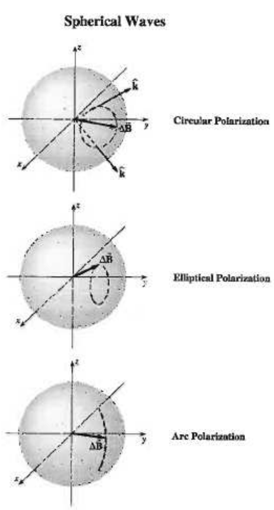

Figure 2. Spherical waves. From top to bottom are circular polarized, elliptical polarized and arc polarized waves. All three waves have constant magnetic field magnitudes. An arc polarized wave is a nonlinear extension of a small amplitude linearly polarized wave. Taken from Tsurutani and Lakhina (2000). See also Tsurutani and Ho (1999).

Figure 1 showed another feature of interplanetary Alfvén waves. Located at the phase-steepened edges of the waves are magnetic field magnitude dips. These have been descriptively called magnetic decreases or MDs. What are these MDs, are they part of the wave themselves or something possibly produced by the waves? Figure 3 is the results of a study of 32 MDs. A biMaxwellian plasma was assumed and the proton temperature both inside and just outside the MDs were measured. It was found that the perpendicular temperatures inside the MDs are higher than outside, indicating that local heating took place. Tsurutani et al. (2002a,b) have made the hypothesis that the Alfvén waves were being rapidly dissipated. The resultant heated plasma was forming diamagnetic cavities, effectively pushing out the magnetic fields to the sides of the MDs.

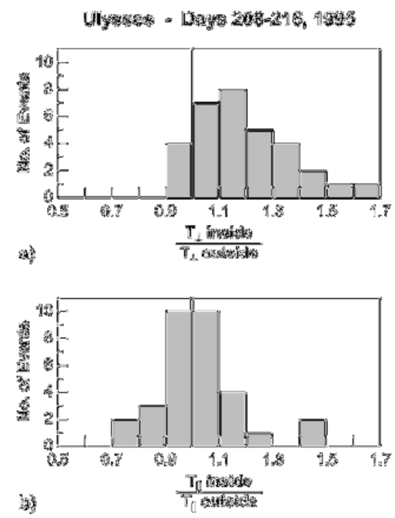

Figure 3. Top panel: the ratio of perpendicular temperature inside MDs to that just outside of it. The perpendicular temperature is higher inside the MD than outside it indicating local heating. Taken from Tsurutani et al. (2002b).

Table 1 shows further evidence that rapid MD and Alfvén wave evolution takes place. This is a comparison of MDs observed at ACE, orbiting the L1 libration point ~0.01 AU upstream of the Earth. Cluster observations of the same MDs are made from orbit around Earth. The temporal (and spatial) scales of the MDs are rapidly evolving with distance and time.

Rate of Phase Steepening

Event (Day)	**MD-ACE/MD Cluster**
33-34	--
43	4.4
50	5.8
51(a)	5.0
51(b)	14.5
76-77	21.3
77	5.5

Table 1. The ratio of temporal thickness of MDs detected at ACE, ~0.01 AU upstream of the Earth and at CLUSTER at the Earth. There is rapid evolution of the MDs. The Table is taken from Tsurutani et al. (2005)

The phase steepened edges of Alfvén waves are probably what most earlier scientists have called interplanetary discontinuities (Smith, 1973a,b; Tsurutani and Smith, 1979; Lepping and Behannon, 1986; Tsurutani and Ho, 1999). However we now think of these as possible intermediate shocks. They Alfvén waves steepened much like magnetosonic waves do, they break much like magnetosonic waves do, and they dissipate (formation of the MDs) much like magnetosonic waves do. The only missing feature that has not been verified is velocity jumps. Perhaps with the more accurate measurements with today's spaceborne instrumentation this could be tested in detail.

Interplanetary Alfvén waves and HILDCAAs

Figure 4 shows interplanetary Alfvén waves detected just upstream of the Earth by the IMP-8 Earth-orbiting satellite instrumentation. The magnetic field is shown in a GSM coordinate system where X points toward the Sun, Y is in the Ω x X direction where Ω is the Earth's north magnetic axis, and Z completes a right-hand system. The amplitude of the Alfvénic fluctuations is ~ 8 nT in an ~8 nT magnetic field. It can be seen in the figure that each time the Bz component turns negative, the geomagnetic AE index increases and the Dst index decreases. Both indices are well established indicators of geomagnetic activity at Earth. The AE index is composed of ~12 equally spaced ground magnetic stations located between ~60° and 7 0° geomagnetic latitude, or the auroral zone. When auroral activity occurs in this zone, east-west currents with intensities up to 10^6 Amperes flow at ~100 km altitude, causing the induced magnetic fields on the ground. When ~10-100 keV energetic electrons and protons get injected into the magnetosphere, the electrons drift from midnight to dawn (and then beyond) and the protons drift from midnight toward dusk due to magnetic field curvature and gradients. The opposite sense of the drift of the oppositely charged particles causes a ring of current called the "ring current". This equatorial current around the Earth causes a decrease in the Earth's field strength at the equator. This is measured by the 4 ~equally spaced ground magnetometer stations used in forming the Dst index.

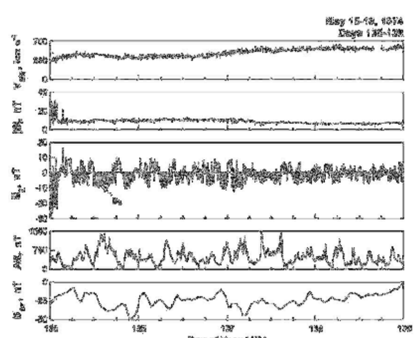

Figure 4. The solar wind speed, V_{sw}, magnetic field magnitude, B_0, the B_z component and two geomagnetic indices, AE and Dst.

Thus the AE increases and the Dst decreases are associated with the interplanetary magnetic field being southward. How does one explain this? The concept of magnetic reconnection (Dungey, 1961; Gonzalez and Mozer, 1973) is well accepted in space physics. When the interplanetary negative B_z magnetic fields press against the positively directed magnetospheric fields on the dayside, magnetic interconnection occurs. The streaming solar wind drags these magnetic fields and embedded plasma in the antisunward forming a long magnetic tail (Tsurutani et al. 1984). When magnetic fields in the tail interconnect, the magnetic tension convects the plasma into the nightside region of the outer magnetosphere. The plasma in the tail has kinetic energies of only ~100 eV to 1 keV. However the inward convection with the maintenance of the first and second adiabatic invariants energizes the electrons and protons to ~10 to 100 keV. The particles are mostly energized by conservation of the first adiabatic invariant, or stated another way, they are betatron accelerated. Thus when the particles reach the outer regions of the Earth's dipolar fields, they have perpendicular temperatures that are higher than their parallel temperatures. Thus the particles are susceptible to temperature anisotropy instabilities (Kennel and Petschek, 1966; Tsurutani and Lakhina, 1997), leading to the generation of electromagnetic ion cyclotron (EMIC) waves from the protons and electromagnetic whistler mode waves (chorus) from the electrons. The waves in turn cause pitch angle scattering of the particles leading to loss in the upper ionosphere at altitudes of ~110 to 80 km (Lakhina et al., 2010). The particle losses excite atmospheric atoms, which then in turn emit characteristic lines of the aurora. This is how the diffuse aurora is created and the reason why the aurora occurs mainly on the nightside near local midnight.

The geomagnetic activity caused by these Alfvén waves present in HSSs are called HILDCAAs (Tsurutani and Gonzalez, 1987). These have been defined to occur outside of the main phase of a magnetic storm and often occur in the "recovery phase" of a magnetic storm caused by a corotating interaction region, or CIR. The CIR magnetic field intensification is caused by the HSS colliding with a slow-speed stream). However from what was stated previously, the magnetosphere is not recovering at all during HILDCAAs, but energy is continuously being injected into the system by the magnetic reconnection associated with the negative z component of the Alfvén waves (Tsurutani et al., 1990; Guarnieri, 2006). In fact there is more energy injected into the magnetosphere during HILDCAA events than during ICME magnetic storms if one averages over the entire HILDCAA interval (Tsurutani et al., 1995; Kozyra et al., 2006; Guarnieri, 2006; Gonzalez et al., 2006; Hajra et al., 2014a).

Chorus and relativistic electrons

The name chorus for the electromagnetic whistler mode ELF cyclotron waves comes from the discrete ~0.2 s "elements" of the waves. These discrete bursts rise in frequency within the ~0.2 s and thus sound like a bird chirping. This name was given to the emission when the waves propagated to the ground and were detected there (K.W. Tremellen, see Storey, 1953).

Relativistic electrons with E > 0.6 MeV, >2.0 MeV and >4.0 MeV have been found to have a one-to-one relationship with HILDCAAs (Hajra et al., 2014b, 2015). This is shown in Figure 5. The zero time is the time of the onset of the HILDCAAs. The appearance of >2.0 MeV electrons occurs after the E > 0.6 MeV electrons and the E > 4.0 MeV electrons after the E > 2.0 MeV electrons. Hajra et al. (2015) have postulated that the acceleration mechanism is a bootstrap type. Higher energy particles are accelerated from lower energy particles, and so on.

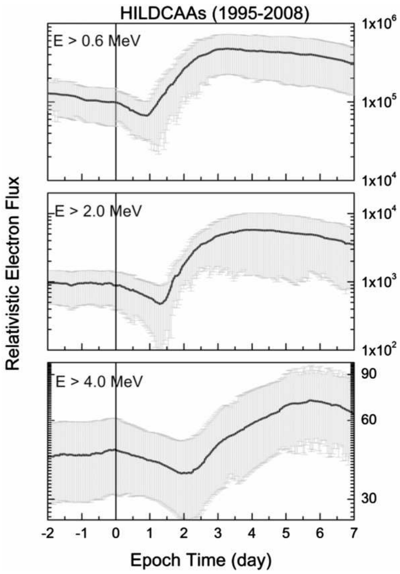

Figure 5. From top to bottom, superposed epoch analyses of the E > 0.6 MeV, E > 2.0 and E > 4.0 MeV electron fluxes. The zero time is the start of the HILDCAA. The figure is taken from Hajra et al. (2015)

The above scenario is in general agreement with current theories of relativistic electron acceleration (Horne and Thorne, 1988; Summers et al., 1988; Meredith et al. 2003; Thorne et al. 2014). It is thought that the high end portion of the HILDCAA injected electrons, E ~ 100 keV are accelerated up to MeV energies by interaction with the chorus. The delay times of ~1 day from E > 0.6 MeV to > 2.0 MeV gives a measure of the efficiency of the acceleration process.

Relativistic electron precipitation and the effects on the ionosphere and atmosphere

Another chorus-energetic electron interaction will be the scattering of particles in their pitch angle relative to the ambient magnetic field. If the particle is scattered so that the pitch is very close to the field direction (called the loss cone) the particle will lose energy by its interaction with upper atmospheric atoms and molecules and will not return to the magnetosphere. Its kinetic energy will be lost by this ionization/excitation process. Chemical reactions can then lead to the production of NO (Thorne, 1980).

It was previously mentioned that ~10 to 100 keV electrons deposit their kinetic energies at ~110 to 80 km altitude. The more energetic the particle, the deeper the penetration. 1 MeV electrons will deposit their energies all the way down to ~50-60 km from the Earth's surface. It has been shown by Kozyra et al. (2006) and Randall et al. (2006) that during cases when there are polar (neutral wind) vortices entraining the NOX molecules created by the electron precipitation, NOX can diffuse down to 30 km altitude over the span of a few months. NOX can cause the destruction of ozone.

Electron microbursts and relativistic electron microbursts

One feature known early in space research is the phenomenon of microbursts, ~0.2 s duration bursts of ~10 to 100 keV electron precipitation (Anderson and Milton, 1964; Lampton, 1967). It has recently been shown how such fast precipitation can occur. Cyclotron resonance between ~10-100 keV electrons and coherent chorus will pitch angle "transport" (not diffused) the electrons. Tsurutani et al. (2009, 2011), Lakhina et al. (2010) and Bellan (2013) have shown that electrons with an interaction with a single ~100 ms chorus subelement can have its pitch angle moved by 5° to 7 °.

Conclusion

Interplanetary Turbulence

We have shown that interplanetary turbulence is full of nonlinear Alfvén waves. These waves phase-steepen and then damp leading to magnetic field magnitude decreases (MDs) such that the medium is "compressive". What is the cause of the growth of the Alfvén waves? The most likely possibility is when the solar wind flows outward from the Sun and the plasma and magnetic fields expand into space, the plasma will become beamed or decompressed due to the conservation of the first adiabatic invariant. This beaming will be subject to the firehose instability or something like it. Waves (Alfvén) will grow and will pitch angle scatter the particles removing this anisotropy. Marsch et al. (1982) have shown by Helios observations that beamed proton distributions do not exist in HSS, contrary to expectations.

This same instability should also be present close to the Sun where the future NASA/ESA Solar Probe Plus and Solar Orbiter spacecrafts will go. Thus we predict that the interplanetary medium will be filled with these nonlinear, compressive waves during these missions.

Stellar turbulence

Stellar winds (Suess and Tsurutani, 2002) are believed to be quite similar to the solar wind. There will be outflow of hot plasmas with embedded magnetic fields flowing away from the stars. Thus one can expect that stellar winds will have embedded large amplitude Alfvén (and perhaps other mode) waves if the flow speed is large enough for instability. One can also expect that the medium will be compressive if Alfvén waves are generated and damped.

MDs, cross-field diffusion and solar flares

The generation of MDs by Alfvén wave damping has been discussed above. However there are consequences of their existence. Energetic E > 1 MeV protons can interact with these magnetic dips with a diffusion across the ambient magnetic field. This interaction is a nonresonant one (Tsurutani et al., 1999) unlike the cyclotron resonant interactions discussed above. Assuming a circular crosssection of the MD with radius a, the particle gyroradius r and the impact parameter d, an analytical expression for the crossfield displacement with a particle-MD impact was obtained.

Da Costa et al. (2013) have done Monte Carlo simulations applied to measured Ulysses MDs. They find that protons with E ~ 2 MeV will diffuse across magnetic field lines at ~ 0.1 the Bohm diffusion rate. Simulations have yet to be done for higher kinetic energies. The distribution of larger scale MDs need to be determined before more Monte Carlo simulations can be performed.

One of the mysteries of solar flare particles is why they have such a large longitudinal spread. At 1 AU the spread can be as large as ~180° in longitude even though the flare site is less than a degree in scale. If MDs exist close to the Sun, the interaction of the flare particles with these structures could explain the wide spread of these particles detected at 1 AU.

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